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PREFACE

This document is an evaluation of the potential for glaciers and glacial flour to fertilize downstream food webs on land and in the ocean. The aim is to consolidate knowledge on the ice to ocean continuum within the ICEBIO consortium through inclusion of selected doctoral candidates' specialties. By doing so, we contribute to fulfill the goal of the ICEBIO consortium and improve the cross discipline understanding of glaciers and glacial flour as fertilizing agents.

INTRODUCTION

The ongoing rise in global temperature poses a significant threat to glaciers and ice sheets with deglaciation as a consequence (Kochtitzky and Copland, 2022). With an increase in mean global temperature of 1.5°C, which is lower than the upper limit set by the Paris Agreement of 2°C, 49% of the global glacial inventory is projected to disappear by 2100 (Rounce et al., 2023, UNFCCC, 2015). The disappearance of the world's glaciers will impact people and wildlife benefitting from the ecosystem services provided directly or indirectly by glaciers. For 1.9 billion people, glaciers constitute a critical freshwater resource (Rounce et al., 2023). Indirectly, glaciers facilitate high productivity in coastal zones with socio-economic impact (e.g. fishery) through local upwelling and nutrient supply (e.g., nitrogen, phosphorus, carbon, silicon and trace metals) (Bhatia et al., 2013, Hawkings et al., 2016, Wadham et al., 2016, Meire et al., 2017, Hendry et al., 2019). Moreover, glaciers have recently been recognized as their own microbial biome supporting nutrient cycling, thereby adding further ecological importance to this realm (Anesio and Laybourn-Parry, 2012). Hence, with the potential disappearance of close to half of the global glaciers by the end of this century, the impact on socio-economics as well as the environmental services related to glaciers, may be significant.

Tied strongly to the socio-economic importance of glaciers, the fertilizing capacity of glaciers and the associated glacial flour has steadily gained focus. Glaciers facilitate inorganic nutrient release from the underlying bedrock via two main processes: 1) Through abiotic or biotic subglacial chemical weathering nutrients and trace metals are released in a dissolved form and transported with meltwater to downstream ecosystems, where they are readily incorporated into the food web by primary producers and bacteria and, 2) via generation of rock particles through physical erosion of the bedrock beneath the ice (Sharp et al., 1999, Wadham et al., 2010, Hendry et al., 2019). The highly reactive, finely ground rock particles, also known as glacial flour, are transported as suspended material within the meltwater runoff (Brown et al., 1996). Additionally, the surface of the glacial flour particulates can be continuously exposed further to chemical weathering processes and thus further the nutrient and trace metal release (Hawkings et al., 2017, Hawkings et al., 2020). The size of the glacial flour, often being < 63µm (silt and clay size fraction), makes the particles highly reactive due to a high surface area to volume ratio, and can potentially lead to prolonged residence time in the water column enabling long distance transport (Andrews, 2000, Wadham et al., 2010, Pryer et al., 2020). The transport of nutrients and trace metal far from the source may enable the glacial processes to support primary production in coastal areas and the ocean (Cape et al., 2019). Depending on lithological composition of the bedrock the mechanochemical glacial processes can deliver essential and often limiting nutrients such as the nitrogen species (ammonium, nitrate and nitrite), phosphate, silicate and trace metals like iron to the recipient waterbodies (Bhatia et al., 2013, Hawkings et al., 2015, Wadham et al., 2016, Hawkings et al., 2016, Hawkings et al., 2017, Cape et al., 2019, Pryer et al., 2020, Hatton et al., 2021, Hatton et al., 2023). In addition to containing beneficial nutrients and trace metals for primary production, glacial flour may also contain trace metals associated with toxicity effects (e.g., Ar, Cd, Ni, Pb etc.) (Galán et al., 2008, Tingey et al., 2025). With the growing interest in the combined usage of glacial flour for agricultural production and geoengineering, increasing crop yield and carbon drawdown through the chemical weathering of the particles, understanding the geological diversity of glacial flour and the potential implications for societal health is important (Gunnarsen et al., 2023, Dietzen and Rosing, 2023).

The potential release of nutrients and trace metals from glaciers and ice sheets are governed by multiple variables such as bedrock composition beneath the ice, glacier size, subglacial hydrology, proglacial landscape features like proglacial lakes, seasonality, among others (Wadham et al., 2010, Bogen et al., 2015, Hawkings et al., 2016, Sharp and Tranter, 2017). Moreover, the type of glaciers – whether it being land-terminating or marine-terminating – can have a profound effects on the physicochemical and biological regimes (Meire et al., 2023). These variables drive the diversity of glacier-influenced environments and are examples of the complex challenges related to predicting nutrient and trace metal cycles and impact on downstream ecosystems.

In this report we synthesize current knowledge on the fertilizing capacity of glaciers and associated glacial flour to downstream ecosystems like lakes, rivers and fjords. We follow the path of nutrients and trace metals through the ice to ocean continuum, starting with subglacial weathering processes. The roles of land-terminating glaciers and proglacial landscape impact on nutrient release and uptake are reviewed, followed by an examination of the effects of marine-terminating glaciers on fjord ecosystems. Throughout, the consequences of continuous deglaciation are considered and potential knowledge gaps exposed to guide future research priorities.

SUBGLACIAL WEATHERING PROCESSES

In the subglacial environment, local physical, chemical and microbial processes govern the nutrient content, as external input is limited, and the environment is characterized by harsh physicochemical conditions. The key source for the release of inorganic nutrients to the subglacial system is the bedrock itself while its mineralogy determines the types and quantities of nutrients and trace elements released during weathering processes (Tranter et al., 2002). Essential for the release of nutrients from the bedrock is the production of the glacial flour. Physical erosion and chemical weathering are closely linked through coupled thermo-mechano-chemical processes, which promote further dissolution of bedrock material (Hatton et al., 2021). The crushing of the bedrock generates fresh amorphous, or poorly crystalline, silica (ASi) and the dissolution of e.g. quartz and aluminosilicates releases Si in form of H_4SiO_4 (Tranter, 2006; Hatton et al., 2019, 2021) and the abrasion of pyrite, the most common sulphide mineral, is an iron source (Tranter, 2003). The weathering and comminution of the bedrock also release nitrogen and phosphorus into the subglacial environment; between 1 and 23 µg P g^{-1} of labile, readily extractable P can be derived from apatite-containing minerals and reactive secondary minerals such as iron-hydroxides (Hodson et al., 2004). Inorganic nitrogen may derive from bedrock containing feldspar or muscovite, releasing nitrogen in form of ammonium (Dixon et al., 2012) . Next to the mineralogy, the residence time of subglacial water affects the extent of rock-water interactions with an increase of dissolved solids with increased residence time (Graly et al., 2014). The source of the meltwater and the flow path it follows also affect water chemistry and its ability to dissolve and transport nutrients (Tranter et al., 1997).

Organic nutrients, such as dissolved organic nitrogen (DON) and phosphorus (DOP) might reach the subglacial environment from surface snow and ice melt, which drain to the glacier bed via moulins and crevasses (Holland et al., 2019). Additionally, microbial processes play a significant role in cycling organic nutrients. Microbial mineralization of organic matter releases inorganic forms of nutrients, which are bioavailable and essential for ecosystem function (Lalli and Parson, 1997). Inorganic nitrogen itself can be recycled with different processes of the nitrogen-cycle like denitrification and nitrification (Hodson et al., 2005; Boyd et al., 2011). Microbial activity can also further mediate chemical weathering reactions; it catalyses sulphide oxidation (Tranter et al., 2002) and microorganisms using DNRA (dissimilatory nitrate reduction to ammonium, a process whereby nitrate is reduced to NH_4^+; Kuypers et al., 2018) may use Fe^{2+} as an electron donor, linking DNRA to subglacial pyrite oxidation (Robertson et al., 2016).

Associated with particles and bedrock, glaciers and glacial flour can release trace levels of metals with both beneficial and harmful impact on organisms (Bhatia et al., 2013, Hawkings et al., 2020, Tingey et al., 2025). One example being mercury where the magnitude of release from glaciated environments are still being debated (Hawkings et al., 2021, Lindeman et al., 2024, Jørgensen et al., 2024). Mercury can be found naturally occurring in the bedrock, deposited atmospherically to the supraglacial environment or bound in organic complexes of ancient organic material beneath the ice (Wang et al., 2022, Kim et al., 2020, Rudnicka-Kępa et al., 2024). Upon release to downstream systems like fjords, mercury can undergo methylation, predominately microbially, thereby generating the highly toxic and bioaccumulating methylmercury (St. Pierre et al., 2018). Previously, the ability to methylate mercury was believed to be a trait reserved for a specific group of bacteria. However, our knowledge on the microbes capable of performing mercury methylation is expanding and the ability is even more widespread than previously thought (Peterson et al., 2023). Considering the highly variable environment of glacier influenced fjords further research is needed to fully resolve the role of glaciers and associated ecosystems in mitigating mercury methylation in order to understand the resonating effects of export and transformation of mercury.

With continued glacial melting, the nutrient fluxes from the subglacial environment into the fjords and oceans are expected to increase in a warming climate; increasing amounts of meltwater may wash out previously sparsely drained subglacial areas and nutrient fluxes currently scale with discharge (Aciego et al., 2015; Hawkings et al., 2015). The current research as part of this doctoral network aims to better understand subglacial nutrient sources in order to make better prediction on how they influence nutrient availability of the glacial runoff. In particular, the effects of comminution on the release of nutrients and the reactivation of pre-weathered subglacial debris, as well as the role of sediment-bound nutrients as a contributor to the pool of the potential bioavailable nutrients, are the subject of current research projects.

LAND-TERMINATING GLACIERS AND GLACIAL FLOUR EXPORT

Land-terminating glaciers make up 60 % of Earth's non-ice sheet glaciated area but account for 74 % of glacial mass loss per year (Hugonnet et al., 2021). Mass loss from land-terminating glaciers is accelerated relative to marine-terminating glaciers (Hugonnet et al., 2021). Initially, these mass decreases coincide with an increased export of freshwater during the melt season up to a peak melt rate (Caretta et al., 2022). This peak is predicted to have been reached for many glaciers already and is projected to be reached for all affected glaciers within the 21st century (Caretta et al., 2022). Following the peak, downstream ecosystems, agriculture, and other human establishments will receive decreasing yearly freshwater inputs (Caretta et al., 2022). Since glacial flour is exported and carried downstream with meltwater from land-terminating glaciers, it is plausible that glacial flour inputs will also peak then fall with consequences for downstream nutrient contributions and temporal turbidity patterns (Egholm et al., 2012).

Unique morphological features in the subglacial and proglacial area of land-terminating glaciers can alter sediment export patterns. For example, proglacial lakes and stream organization can act as filters to sediment transport, temporary decreased transfer capacity can lead to settlement events, and subglacial sediment can build up then export in mass evacuation events (Hervé et al., 2022, Mancini et al., 2023). However, early research indicates that there is decreased impact of morphological variables to fine suspended sediment, like glacial flour, compared to coarser sediment (Mancini et al., 2023). Whereas marine-terminating glacial flour and associated nutrients deposit into an aquatic ecosystem directly, the deposition fate of suspended glacial flour in melt-streams is prone to greater spatial variability.

Glacial flour exported from land-terminating glaciers can elicit meaningful effects in downstream aquatic ecosystems. For example, Peter and Sommaruga (2016) reported that proglacial lakes with high turbidity due to suspended sediment housed unique microbial community members that were not detected in the proglacial lakes that no longer received turbid meltwater inputs due to glacial retreat (Peter and Sommaruga, 2016). It is possible that the glacial meltwater and suspended glacial flour sediment provide a selective fertilization effect in addition to blocking light required by autotrophs (Peter and Sommaruga, 2016). Thus, loss of glacial flour inputs due to terminal glacial retreat may have detrimental effects on uniquely adapted microbial biodiversity in glacial environments. However, recent projections indicate that most glacial freshwater and forefield sites globally will experience an overall increase in species richness and diversity of microorganisms, animals, and plants as glaciers retreat (Cauvy-Fraunié and Dangles, 2019). Communities of organisms expected to “win” with glacial retreat consist of generalists who may colonize from downstream (Cauvy-Fraunié and Dangles, 2019). Those that “lose” consist of specialist species that are adapted to the conditions of a glacial ecosystem with high glacial flour input (Cauvy-Fraunié and Dangles, 2019).

In glacial forefields, sediments, including deposited glacial flour, provide a site for ecological succession (Bradley et al., 2014, Bradley et al., 2016, Raffl et al., 2006, Wojcik et al., 2021, Bajerski and Wagner, 2013). Abiotic weathering, resulting from physical and geochemical processes, and biotic weathering, resulting from the biomechanical and biochemical activity of microorganisms, plants, and other life, drive the formation of soil (Wild et al., 2022). The initial colonizers of glacial sediments are microorganisms which are tolerant to the low initial organic matter content and contribute to the gradual accumulation of organic carbon and nitrogen during soil formation (Guelland et al., 2013, Bradley et al., 2014, Bradley et al., 2016). While incubating glacial forefield granite crushed to a grain size of < 0.6 mm with microbial isolates from the same forefield, Frey et al. (2010) observed weathering activity resulting from microbially produced oxalic acid which freed Fe, Ca, K, Mg, and Mn (Frey et al., 2010). These elements may serve as essential cofactors in microbial enzymatic processes and are also considered essential nutrients for plant growth (Dai et al., 2023, Singh et al., 2022). Thus, depending on its geochemical composition, glacial rock flour may provide a fertilization input to both microorganisms and plants in the glacial forefield upon weathering. In an experiment on the use of glacial rock flour from land-terminating glaciers in agriculture, soybean yield from a nutrient-poor potting matrix was significantly increased compared to control application of N, P, and K alone and in combination (Tingey et al., 2025). This indicates effective delivery of essential plant nutrients from the basaltic and metamorphic/sedimentary glacial flours used (Tingey et al., 2025). Similar nutrient delivery from glacial flour may be occurring for plants colonizing glacial forefields. However, accounting for the bedrock composition is essential to understanding its potential effects since for example arsenic derived from glacial flour has been seen to transfer to crops, potentially posing a threat to consumers (Tingey et al., 2025).

Research on the effects of glacial flour derived from land-terminating glaciers would benefit from capturing additional bedrock types and increased spatial and temporal variability in sampling. Though several studies have assessed species succession in glacial forefields, analyses targeted to glacial flour-sized fractions in the ecosystem would yield more specific knowledge on the fertilization contributions of this sediment type. Integration of geochemical/geophysical and ecological research methods is needed to assess the fertilization axis between glacial flour, microorganisms, and higher order ecosystem members such as plants. Additionally, more observations on glacier-fed freshwater systems will improve our understanding of biodiversity changes and food web shifts as land-terminating glaciers retreat and waters gain and lose turbidity.

MARINE-TERMINATING GLACIERS AND GLACIAL FLOUR IMPACT IN FJORD-SYSTEMS

Ending in fjords or the ocean, marine-terminating glaciers, also known as tidewater glaciers, have a unique impact on the associated ecosystems. Localized upwelling, due to buoyancy differences between fresh subglacial meltwater and marine water near the glacial front, drives high production zones (Meire et al., 2017, Hawkings, 2021). When a mix of nutrient rich marine bottom water and fresh glacial meltwater reaches the euphotic zone, it generates a “sweet spot” in nutrient composition for primary production (Meire et al., 2017). Cape et al. (2019) found elevated concentrations of nitrate, phosphate and silicate near marine-terminating glacial fronts of the Greenland Ice Sheet compared to continental shelf waters measured at same depths.

The impact of the presence of glaciers is especially evident for export of silicates. As described above, mechanochemical processes related to glaciers can enable release of silicate to downstream ecosystems (Hatton et al., 2021). Furthermore, the increase in salinity have been described to increase the dissolution of amorphous Si from silica particles due to the increase in alkali and alkaline earth metals (Dove et al., 2008, Hawkings et al., 2017). Silicate is paramount for the growth of siliceous organisms in the oceans, such as diatoms (Tréguer et al., 1995). This phytoplankton group, that constitutes upward of 40% of all phytoplankton in the oceans, links the silica, carbon cycle and biological pump together through carbon sequestration performed by the diatoms and the later sink out of dead individuals (Tréguer et al., 2018). Furthermore, the elevated nutrient levels that leads to increased primary production, e.g., phytoplankton groups like diatoms, increases the abundance of higher trophic levels such as zooplankton, which again impacts animals like crustaceans, fish, birds, seals and whales (Meire et al., 2017). For example, an increase of halibut landings has been observed in relation to marine-terminating glaciers of the Greenland Ice Sheet (Meire et al., 2017). This increase was ascribed to the nutrient upwelling promoted by subglacial and supraglacial discharge below sea-level. Halibut landings constituting 42% of the fisheries income in Greenland, the economical contribution of the presence of marine-terminating glaciers are significant (Meire et al., 2017). Concurrent with the upwelling of nutrient rich bottom water, currents may also transport entrained organisms like zooplankton and fish to the surface (Hop et al., 2023). This transport of smaller marine organisms generates a feeding spot for birds like black-legged kittiwakes (Bertrand et al., 2021, Hop et al., 2023). Moreover, seals have been observed in the vicinity of upwelling zones, where they prey on larger marine organisms entrained in the upwelling current (Lydersen et al., 2014, Everett et al., 2018). Hence, the marine-terminating glaciers support the ecosystem from bottom to top through the buoyancy driven upwelling.

Despite the fortunate conditions occurring near marine-terminating glacial fronts, the meltwater driven sediment concentration in this area has the potential to disrupt any benefits for primary production. High glacial flour concentrations will lower the light penetration depth and counteract the benefits of increased nutrient concentrations (Halbach et al., 2019). However, as sediment concentration drops throughout the fjord, when the particles sink out, the light penetration increases, allowing for primary production to happen further downstream (Zajączkowski, 2008, Meire et al., 2017). The sinking rate of particles are governed by the density of the particle itself, which for glacial flour can vary greatly depending on lithology, with denser rock types like gneiss sinking out faster than lighter ones like sandstone - staying afloat for longer distances (Zajączkowski, 2008, Halbach et al., 2019). Because of the high production of particles associated with glaciers, large amount of glacial flour can be deposited in the vicinity of marine-terminating glaciers, which may impact the formation of benthic communities negatively through the continuous physical disturbance (Wlodarska-Kowalczuk et al., 2005). On the other hand, continuous dissolution and occasional resuspension of deposited glacial flour, aided by the local upwelling current, could potentially supply additional nutrients to the euphotic zone. However, the importance of the benthic flux, transport and remineralization processes related to marine-terminating glacial front environments are still an understudied area (Wehrmann et al., 2014, Hawkings et al., 2017). Further research into the extent to which glacial flour, suspended or sedimented, support or hamper primary production through nutrient dissolution and physical disruption would strengthen the knowledge on the implications of deglaciation on the food web in coastal areas.

As a consequence of deglaciation, marine-terminating glaciers are retreating onto land. From 2000 to 2020 ~85% of all marine-terminating glaciers on the Northern Hemisphere have been retreating and 123 of the 1704 marine terminating glaciers transitioned to land-terminating in the same period (Kochtitzky and Copland, 2022). With this shift follows an array of changes to the environment (Meire et al., 2023). When marine-terminating glaciers disappearing so does the local upwelling and the increased nutrient deliverance to the euphotic zone (Meire et al., 2023). Because of the lack of mixing of water mases, the meltwater run off from the land-terminating glaciers will spread on top of the denser marine waters, generating a freshwater lens with potential high sediment load blocking out light (Meire et al., 2023). A comparison study from two Greenlandic fjords influenced either by land- or marine-terminating glaciers, revealed distinct differences in phytoplankton community composition and bacterial abundance (Meire et al., 2023). The fjord influenced mainly by marine-terminating glaciers showed higher abundance of diatoms which supports the growth of larger zooplankton species. Contrasting, the fjord influenced by land-terminating glaciers showed overall lower productivity, was dominated by smaller phytoplankton species, e.g., picophytoplankton and had an increase in bacterial abundance (Meire et al., 2023). A shift in phytoplankton community composition from larger to smaller species, may impact carbon sequestration and nutritional benefits for dependent animals (Meire et al., 2023).

CONCLUDING REMARKS

Two thousand and twenty four was the year that the average global temperature exceeded 1.6°C as reported by the Brekley Erath Group, which is 0.1°C higher than the threshold set by the Paris Agreements to reduce the impact of climate change (UNFCCC, 2015). Year by year environmental records are broken and the world is changing at an unprecedented pace. The effect of the rise in global temperature is already evident with the disappearance of 124 out of 1704 marine-terminating glaciers on the Northern Hemisphere over a time span of 20 years (Kochtitzky and Copland, 2022). The highly specific local upwelling driven by marine-terminating glaciers is crucial to the high production seen in these areas and have a direct impact on the food web, from the tinniest to the largest members – from bacteria to whales (Lydersen et al., 2014, Meire et al., 2017, Bertrand et al., 2021, Sejr et al., 2022, Hop et al., 2023, Meire et al., 2023) Moreover, the shrinking of land-terminating glaciers, which constitutes a critical freshwater source, may have direct societal impact (Rounce et al., 2023). The appearance of proglacial landscape, including proglacial lakes, as glaciers retreat may lead to loss of glacier associated microbial communities (Peter and Sommaruga, 2016). However, it is expected that the increased formation of proglacial landscape overall will increase the biodiversity (Cauvy-Fraunié and Dangles, 2019).

On the backdrop this report, the importance of continuous protection and research of glacial environments in order to maintain the ecological services provided through these ecosystems is evident. Increasing our knowledge on glacier influenced environments is detrimental to generate robust predictions of potential changes to come.

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